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Offshore floating vertical axis wind turbines, dynamics modelling state of the art. part I: Aerodynamics

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ABSTRACT

The need to further exploit offshore wind resources has pushed offshore wind farms into deeper waters, requiring the use of floating support structures to be economically sustainable. The use of conventional wind turbines may not continue to be the optimal design for floating applications. Therefore it is important to assess other alternative concepts in this context. Vertical axis wind turbines (VAWTs) are one promising concept, and it is important to first understand the coupled and relatively complex dynamics of floating VAWTs to assess their technical feasibility. A comprehensive review detailing the areas of engineering expertise utilised in developing an understanding of the coupled dynamics of floating VAWTs has been developed through a series of articles. This first article details the aerodynamic modelling of VAWTs, providing a review of available models, discussing their applicability to floating VAWTs and current implementations by researchers in this field. A concise comparison between conventional horizontal axis wind turbines and VAWTs is also presented, outlining the advantages and disadvantages of these technologies for the floating wind industry. This article has been written both for researchers new to this research area, outlining underlying theory whilst providing a comprehensive review of the latest work, and for experts in this area, providing a comprehensive list of the relevant references where the details of modelling approaches may be found.

Contents

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1. Introduction

With the need to increase renewable energy's share in global energy production and to exploit offshore wind resources, wind farms are moving further and further offshore into deeper waters. In water depths greater than 50 m, bottom-mounted (i.e. fixed) support structures for offshore wind turbines do not remain the most economically viable option [1]. A transition from fixed to floating support structures is essential for deep offshore wind farms to become economically viable in the near future.

The onshore wind industry has reached a relatively mature level, with the majority of large scale wind turbines sharing the same configuration: horizontal axis of rotation, three blades, upwind, variable-speed and variable blade pitch (with feathering capability). This has been the result of several decades of research and development, and originally several configurations had been considered, including horizontal axis wind turbines (HAWTs) with a different number of blades, but also vertical axis wind turbine (VAWT) configurations. The conventional design emerged as the optimum techno-economic trade-off for the onshore large scale wind market.

The same "evolutionary process" did not take place for the offshore wind market, substituted by a "marinisation" of the trusted configurations used for the onshore market. It has been implicitly assumed that, despite the very different environmental conditions of an offshore environment, the optimum configuration for the wind turbine is the same i.e. the conventional three bladed, upwind, horizontal axis wind turbine. This has been implicitly assumed not only for the bottom-mounted offshore wind turbine configurations, but also for proposed floating systems. In fact two prototype floating wind turbines, Hywind [2] and WindFloat [3], made use of 2–2.3 MW HAWT machines design for fixed on- and offshore foundations.

It is therefore important to assess the technical and economic feasibilities of alternative concepts for the offshore floating wind industry in order to ensure that the most suitable configurations are employed, with VAWTs being one promising concept that could complement HAWTs in offshore wind industry. The first step is to understand the complex dynamics of such a floating system subjected to the harsh offshore environment. As part of this task, a series of articles have been developed to present a comprehensive literature review covering the various areas of engineering expertise required to understand the coupled dynamics involved in floating VAWTs. This first article focuses on aerodynamic modelling of VAWTs and is organised as follows:

- Section 2 gives a brief history of the development of VAWTs
- Section 3 compares VAWTs to the more conventional HAWTs on a number of aspects highlighting their advantages and disadvantages
- Section 4 discusses and compares the different aerodynamic modelling techniques in depth
- Section 5 outlines current implementations by researchers
- Section 6 presents some conclusions.

2. A brief history of VAWT developments

As outlined by Shires [4], the modern onshore VAWT was developed in the years following the first oil crisis of 1973. These designs were based on a 1922 patent by the French engineer Georges Darrieus, with straight or curved blades rotating about a vertical shaft.

The 1970s and 1980s saw a substantial amount of research and development, particularly in the United States and Canada, that led to a number of curve bladed (or Φ-rotor) Darrieus turbines. The largest onshore VAWT, built in 1986 in Québec, Canada, was the Éole Darrieus Wind Turbine shown in Fig. 1, with a height of 96 m. With a rated maximum power of 3.8 MW, it produced 12 GWh of electric energy during the 5 years it operated but was shut down in 1993 due to a bearing failure.

Attempts to commercialise these VAWT developments were made in the United States during the 1980s by FloWind Ltd. A number of onshore wind farms were developed and worked efficiently, although they experienced fatigue problems with the blades [5].

The straight-bladed Darrieus turbine or H-rotor was largely developed in the UK by Peter Musgrove during the 1980s and 1990s. The concept of the H-rotor was to reduce blade manufacturing costs and simplify the support structure, relative to the Φ-rotor, with a shorter tower and eliminating the need for guy wires [6]. A number of onshore prototypes were constructed in the

Fig. 1. 3.8 MW Éole VAWT Φ-rotor.

Fig. 2. 0.5 MW VAWT-850 H-rotor.

UK, the largest being a 500 kW machine shown in Fig. 2 built in 1990 [7]. However, this prototype suffered a blade failure after a few months of operation due to a manufacturing defect that set back any further VAWT deployment efforts [8].

The V-rotor, first proposed by Olle Ljungstrom in 1973 [9], aimed to mimic the lower half of an Φ-rotor. It had the advantage of a shorter tower than a Φ or H-rotor and eliminated the horizontal (and therefore dragging) struts and supporting arms of Φ and H-rotors.

Despite these onshore VAWT developments, problems with fatigue failures due to the highly cyclic loads and a low demand in the wind energy market in the United States contributed to a fall in financial support for VAWT development projects in the 1990s. However, the need for larger offshore turbines that can utilise economies of scale and a need for deep water solutions have led to a recent resurgence of interest in VAWTs. In a recent review of VAWT technologies and economics, Sandia concluded that VAWTs "have significant advantages over HAWTs in off-shore applications" [10] and that H or V-rotor designs are likely to be more cost-effective. Furthermore there have recently been a small number of projects investigating floating VAWT concepts, namely the NOVA project [11], EU-FP7 DeepWind project [12] and EU-FP7 INFLOW project [13].

3. VAWTs versus HAWTs

In this section VAWTs are compared to HAWTs for a number of different aspects, highlighting both the advantages and disadvantages of this technology. Other publications such as Paraschivoiu [14], Jamieson [15] and Islam et al. [16] have also attempted to compare HAWTs and VAWTs. Fig. 3 gives the reader a first glance at the differences between HAWTs and VAWTs.

State of Technology. Since HAWTs have been the main focus of the wind energy industry over the past decades, its state of technology is more mature than that of VAWTs, with a large number of successfully deployed projects and the formation of a dedicated supply chain. VAWTs were investigated in the late 20th century but interest was lost mainly due to fatigue issues and low efficiencies [10].

Conversion Efficiency. The maximum theoretical efficiency of any wind turbine is 59.3% (the Betz limit) [17]. HAWTs are inherently more efficient than VAWTs with power coefficients of up to approximately 50% compared to approximately 40% for VAWTs. This should not be seen as the ultimate deciding factor between the two configurations as many other factors affect the final cost of electricity. Recent research by Kinzel et al. [18] found that by placing two VAWTs in close proximity to one another, the conversion efficiency may actually increase when compared to single VAWTs. This may further the case for VAWTs and affect the design of future VAWT wind farms.

Upscaling. A major factor in designing floating wind turbines is scalability, as the system is more cost-effective at larger scales. HAWTs have a limiting factor due to gravitational fatigue since the blades undergo tension-compression cycles as the rotor rotates [17]. VAWTs do not undergo this phenomenon and so far do not seem to have any major obstacles in upscaling.

Fatigue. Whilst HAWTs have gravitational fatigue issues, VAWTs produce a cyclically varying torque that can have adverse effects on the transmission and control systems [15]. Whilst this produces high-frequency fatigue cycles in small-scale VAWTs, multi-megawatt VAWTs would rotate at a few revolutions per minute, where it would not be such a significant problem. Also with advances in materials technology, fatigue can more easily be remedied today.

Machinery Position. A very important aspect is the position of the transmission and generation system. In an HAWT it is at the very top of the tower (considering the latest offshore wind turbines, the nacelle weight around 400 t, and is around 100 m above the ground (see for example Vestas V164–8.0 MW), inducing greater bending moments and motions on the tower, requiring larger, stronger structures. This would also require a larger floating platform to deal with the larger loads. On the other hand, VAWTs usually have the transmission and generation systems at the bottom [19], requiring small support structures and complying more with fundamental naval architecture principles.

Extreme Conditions. HAWTs are usually shut down in wind speeds greater than 25 m/s whilst VAWTs, in theory, should be able to operate in wind speeds up to 65 m/s [16]. VAWTs are also much more insensitive to extreme weather conditions such as heavy snow, freezing rain, frost, salt, sand and humidity [16].

Packing Factor. In wind farms using HAWTs, the turbines are usually placed a distance of up to ten times their diameter from one another due to the effect of their wakes [20], leaving large amounts of unexploited space in between them. With VAWTs it has been postulated that their wake dissipates much quicker than those of HAWTs, allowing them to be packed closer together [21]. In fact Kinzel et al. [18] found that for a single operating VAWT, the flow velocity required a distance of four rotor diameters behind the turbine to reach 95% of the freestream velocity, whilst approximately fourteen rotor diameters are required in the case of a HAWT for the downwind flow to reach 95% of the upwind velocity [18]. Whilst this was a preliminary study into the wake characteristics of VAWTs, it is indicative of the potential benefits of such turbines in utilising available wind farm site area.

Installation Issues. Floating wind turbines provide the possibility of the majority of construction being done dockside rather than on site. Whilst this is beneficial to both HAWTs and VAWTs, the former still require very large cranes to mount the machinery and blades, increasing the capital costs [15]. This aspect is also an advantage over fixed-support wind turbines, as they are usually assembled on site.

4. Modelling approaches

The major aerodynamic modelling approaches used for VAWTs are the Blade Element Momentum (BEM) model, Cascade model

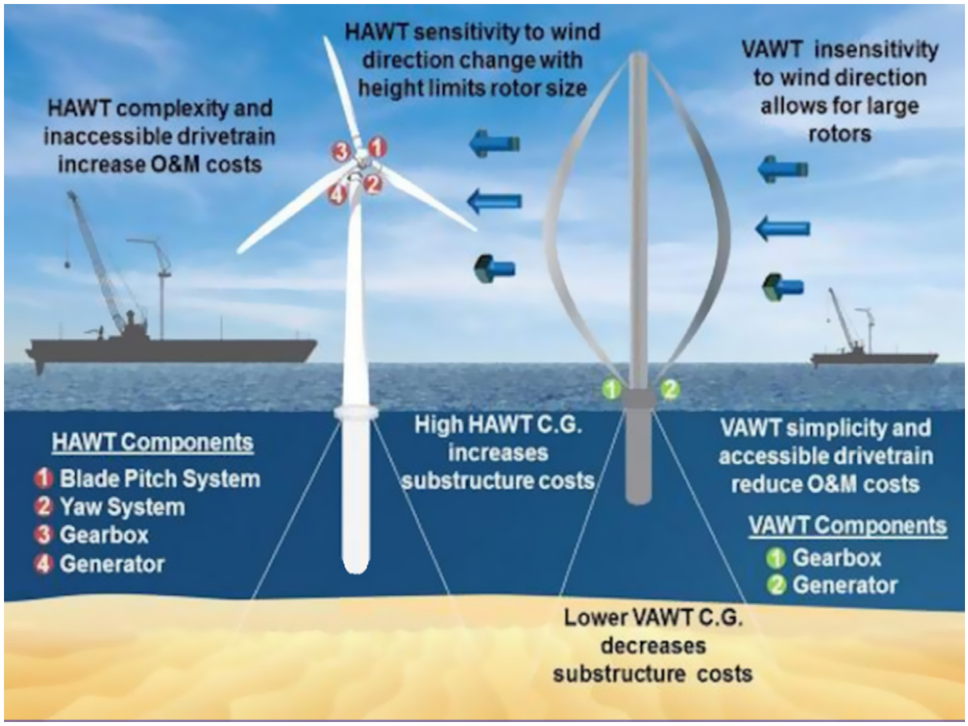

Fig. 3. Conceptual comparison between floating horizontal and vertical axis wind turbines, adapted from http://energy.sandia.gov/?page_id=344.

and Vortex model [22], whilst panel methods also seem to be a promising approach for modelling VAWTs [23–26]. Methods such as Reynolds–averaged Navier-Stokes (RANS) computational fluid dynamics (CFD) are not discussed here as they are too computationally intensive to form part of a methodology used for the conceptual and preliminary design of floating wind turbine systems.

4.1. Blade element momentum models

This model is based on equating the streamwise momentum change across the turbine to the forces acting on the turbine blades [27]. The first momentum model for VAWTs (based on Glauert's theory for propellers) was developed by Templin [28], where a single streamtube passing through an actuator disk was used to represent the VAWT, similar to Froude's momentum theory applied to HAWTs.

Subsequently a multiple streamtube model was developed concurrently by Wilson and Lissaman [29] and Strickland [30], where now the flow through the actuator disk is split into a number of equal streamtubes that are independent of one another. The momentum equation is thus applied to each streamtube and the blade elements that pass through that streamtube.

The double-multiple streamtube (DMST) model as described in [31] is the most elaborate variant, and has the best agreement with experimental results [14;22] for momentum models. Besides having multiple streamtubes, this model also performs the momentum calculations separately for the upwind and downwind half-cycles of the rotor, shown schematically in Fig. 4. This enabled the analysis of more complex shapes without a loss in numerical accuracy (see e.g. Shires [32]). Subsequently, further improvements to include secondary effects such as dynamic stall and tip losses were made in [14,32–34], as will be further elaborated in Section 4.5.

Fig. 5 outlines a typical time-stepping scheme for the DMST model as implemented by Shires [32]. At each time increment, the process involved calculating the relative velocity and angle of attack at each collocation point. With these in hand the aerofoil lift and drag characteristics are obtained from a database of the static aerodynamic loads that are generally derived from wind tunnel testing. These forces are then updated to take into account dynamic stall and other three-dimensional effects. Finally the momentum loss over the upwind and downwind cycles (see Fig. 4) is calculated, and the blade loads are integrated before moving on to the next time step.

Although this model gave good agreement with experimental results of the overall performance for light-loaded, low-solidity rotors, it suffers both numerically and in accuracy when the rotor has a high solidity, is heavily loaded and/or is operating at high tip-speed ratios [14;22;27].

The Actuator Cylinder flow model approach proposed by Risø National Laboratory at the Technical University of Denmark [35] represents an extension of the actuator disc concept. Instead of considering the momentum balance within streamtubes, an energy balance approach is considered for the swept surface of a VAWT rotor acting as an actuator cylinder.

4.2. Cascade models

These models are based on cascade theory used in turbomachinery design (see e.g. [36;37]), and were first applied to VAWTs by Hirsch and Mandal [38]. The blades of the rotor are assumed to be positioned on a plane surface, known as a cascade, with the spacing between adjacent blades equal to the rotor circumference divided by the number of blades, as illustrated in Fig. 6. The development and implementation of this model then follows a similar route as the DMST momentum model.

An improvement over the model presented by Hirsch and Mandal was proposed by Mandal and Burton [39] to include flow curvature and dynamic stall. These modifications allowed the model to more accurately represent the flow and loading characteristics experienced by a VAWT in reality, providing for local blade force predictions and generated power in better agreement with experimental data in the study.

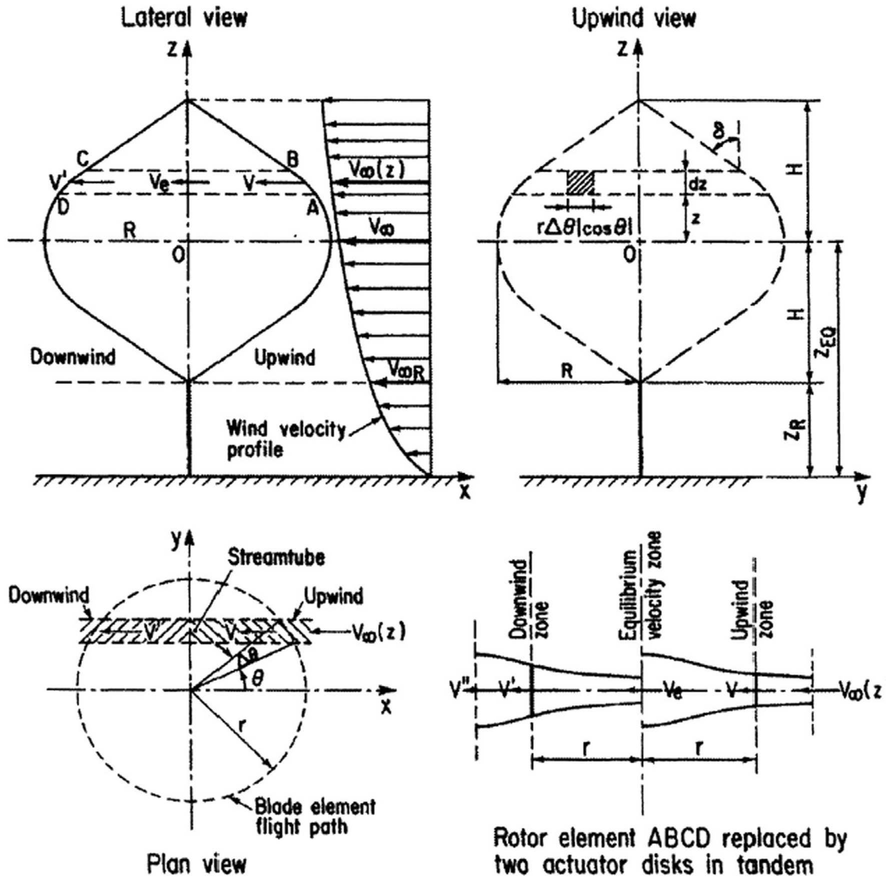

Fig. 4. Schematic diagram of the Double Multiple Streamtube Model [37].

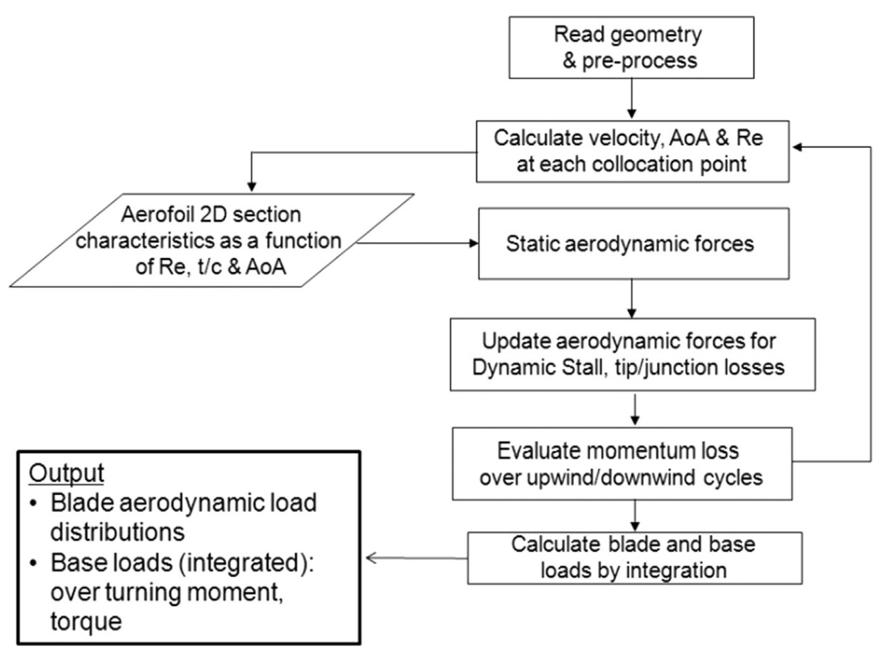

Fig. 5. Typical time-stepping scheme for blade element momentum models [35].

Although this model requires more computational time than its momentum model counterpart, it provides more accurate overall values for both low and high solidity rotors [22], and does not suffer convergence problems at high solidities and high tip speed ratios [22]. According to [38], momentum models are not suited for calculating instantaneous blade forces and wake velocities for high solidity rotors and for high tip speed ratios. This is due to the fact that momentum models assume steady-state flow (which is not necessarily the case for floating VAWTs, where platform-induced motion and turbulent wind create unsteady flow conditions), where average the flow momentum losses through the VAWT rotor over one revolution.

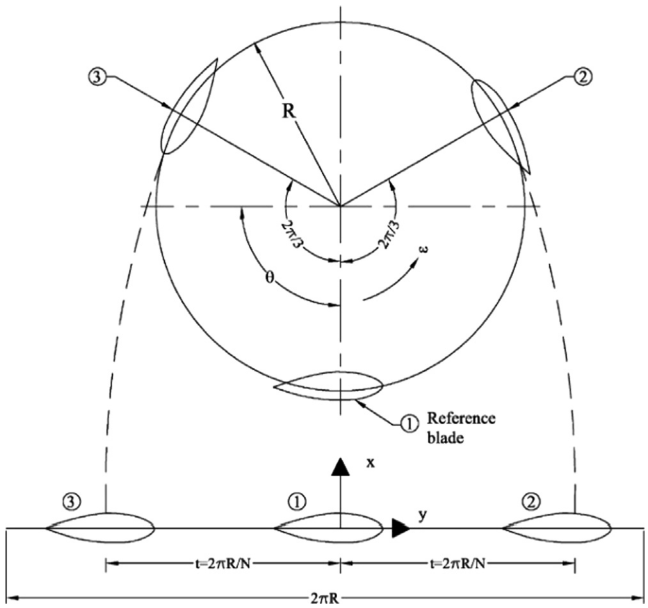

Fig. 6. Cascade model configuration, adapted from Islam et al. [25].

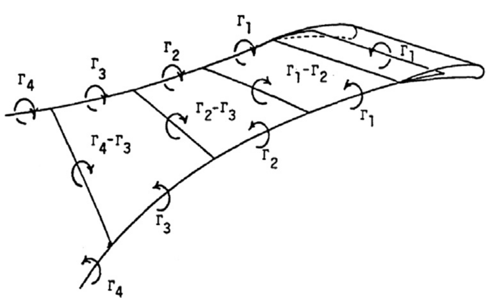

Fig. 7. Vortex element schematic diagram with progression of shed vortices, adapted from Strickland et al. [30].

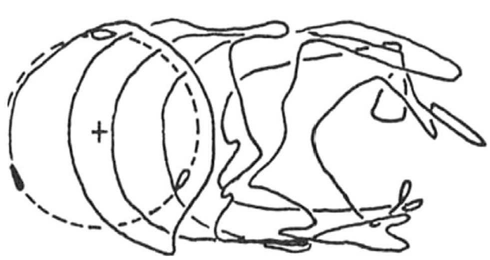

Fig. 8. Plan view of a typical blade trailing edge wake simulation of a three-bladed VAWT, adapted from Strickland et al. [30].

4.3. Vortex model

Vortex models assume potential (i.e. inviscid) flow. The velocity field in the vicinity of the rotor is obtained by calculating the influence of vorticity in the wake of the blades [14;22]. In this model the aerofoil blades are split up into a number of elements, and each element is replaced by a bound (or substitution) vortex filament, also known as a lifting line [27]. With each time step vortices are shed and these influence the induced velocity of the blade, as illustrated in Fig. 7.

Two dimensional vortex models for VAWTs were first proposed by Larsen [40], and further two dimensional models were presented by Fanucci and Walter [41], Holme [42] and Wilson [43]. These models made several assumptions such as: high tip-speed ratios, lightly loaded rotor, small angles of attack to ignore stall, and high height-to-diameter ratios (for two-dimensional flow). These assumptions limited the vortex models to a specific range of applications and operating conditions.

The first three-dimensional model was presented by Strickland et al. [27]. Further improvements by Strickland et al. [44] included dynamic effects, such as dynamic stall, pitching circulation and added mass. When compared with experimental results, it was found that there was good correlation for instantaneous blade forces and near-wake velocities. Some discrepancies were attributed to shortcomings in the experimental set-up by Strickland et al. [27].

To further enhance this free-vortex model, Cardona [45] incorporated flow curvature as well as modifying the dynamic stall model. These modifications were found to improve the correlation between results for both overall power coefficient values and instantaneous blade forces. Vandenberghe and Dick [46] presented a modified analysis of this model using a multi-grid approach consisting of solving the Poisson equation on a rectangular grid rather than using the Biot-Savart law to calculate the wake-induced velocity field. It was found that this approach reduced computational times and was proposed for the parametric optimisation of VAWTs and for pitch-controlled turbines.

Another modification to the free-vortex model was performed by Beyer et al. [47] using curved vortex filaments rather than straight ones though problems with convergence of the straight line and curved filament models at fine discretisations were encountered.

Another approach was taken by Ponta and Jacovkis [48] to combine the free-vortex model with a finite element analysis of the flow in the vicinity of the rotor. The concept behind this approach was to split the analysis into two separate regions: macro and micro models. This helped to avoid certain shortcomings of the abovementioned vortex model, and showed better agreement with experimental results. One disadvantage of this approach was that it does not cover all stall phenomena.

Sebastian [49] recently showed the potential of applying vortex models to floating horizontal axis wind turbines. The ability of vortex models to accurately predict the velocities and evolution of the near wake (see Fig. 8), allow for more precise simulations of the wake-rotor interactions. These interactions may prove to be an important factor, as they may significantly affect the aerodynamic performance of the floating turbine. The influence of multiple turbines on one another may also be investigated with this model, as it has been observed through experimentation by Kinzel et al. [18] that two closely spaced VAWTs may actually improve power production compared to a single operating VAWT, depending on their relative position to one another and the incoming wind flow. In certain configurations a VAWT pair was found to generate 5–10 per cent additional power as compared to isolated VAWTs. Ilin et al. [50] found that whilst the vortex model does not significantly improve power predictions when compared to the momentum models, it does more accurately predict blade loads, which may be of more importance when investigating the coupled dynamics of floating VAWTs.

Scheurich and Brown [51] also recently used a vorticity transport model (originally developed for helicopter applications) to investigate the overall turbine efficiency for different VAWT configurations in both steady and unsteady wind conditions. The use of helical/twisted blades was found to improve turbine performance as compared to straight blade. This aerodynamic model was compared to experimental data by Scheurich and Brown [52] and Scheurich et al. [53] and found to be in very satisfactory agreement based on blade aerodynamic loading and predicted power curves.

Fig. 9 presents a typical time-stepping scheme for a vortex model, based on codes developed by Strickland et al. [27] and Sebastian [49].

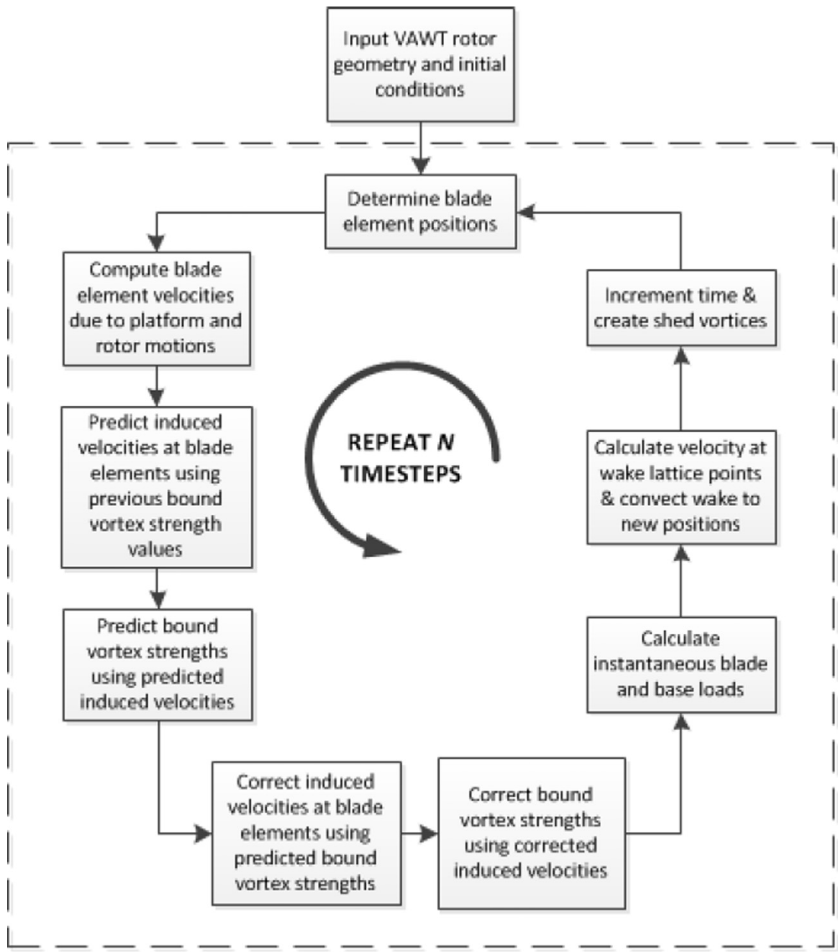

Fig. 9. Typical time-stepping scheme for vortex models.

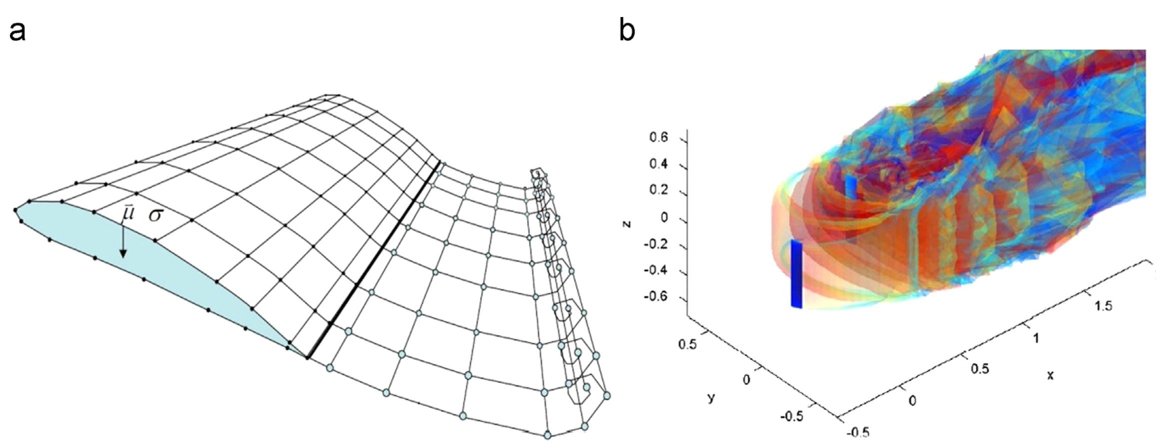

Fig. 10. (a) Panel discretisation of a VAWT blade section and wake roll up; (b) sample visualisation of a 2-bladed VAWT panel model simulation using the Unsteady free-wake Multi-body Panel Method (UMPM) [58,59].

4.4. Panel models

This approach is based upon discretising the 3D surface of the rotor into a number of panels and assumes a potential flow regime, as shown in Fig. 10a. On each panel, an ideal flow element (such as a source or doublet) is placed with a prescribed strength and the Laplace equation is subsequently solved for the inviscid and incompressible flow. Panel models can be considered as an extension to vortex models. Vortex models represent an aerofoil as a single blade element, using look up tables for lift and drag characteristics to derive the corresponding vortex strength of the element. Panel models represent the aerofoil using a series of body conforming panels at which 3D flow properties are calculated and consequently are generally more accurate. This method has been applied extensively in naval hydrodynamics as well as aircraft aerodynamics, as reviewed by Erickson [54].

The relatively fast computational time in comparison to using higher-fidelity CFD simulations is one of the main benefits of this method. Another major benefit of panel method is that any geometry can be modelled, and does not rely on the interpolation/extrapolation of two-dimensional aerofoil data obtained through experiment or CFD.

Eliassen and Muskulus [26] implemented and validated a fast hybrid vortex-panel model on a general purpose graphical process unit GPU, showcasing the potential of this model and computational strategy. A three-dimensional panel method for VAWTs was first presented by Dixon et al. [25] and was then validated by Dixon [55] and Ferreira et al. [56]. Dixon [55] used Stereo-PIV experimental results and smoke-trail studies for a straight-bladed VAWT to demonstrate the validity of the model. This model was developed to analyse and understand the development of the near wake and tip vortices of a VAWT. A sample visualisation of a 2-bladed VAWT simulation using this model is given in Fig. 10b.

Since this type of model is based on potential flow, viscous effects such as stall are not implicitly included. Therefore there is a need to incorporate a boundary layer model such as the lag-entrainment method (see e.g. Green et al. [57]). Although a viscous coupled panel method is available for HAWT aerodynamics (e.g. NEWPAN [58]) the authors are not aware of a similar development for VAWTs. Fig. 11 outlines a typical time-stepping scheme for a panel model, as implemented by Dixon [55]. As can be seen, it is more involved than the previous models described.

4.5. Modelling secondary effects

As described previously, the inclusion of secondary effects allows for better prediction of the power performance and blade forces of a VAWT. In the following sections the various secondary effects and their significance shall be briefly outlined.

4.5.1. Dynamic stall

The dynamic stall phenomena results from unsteady lag effects as an aerofoil experiences a rapidly changing pitch angle. Initially, as the pitch angle increases beyond the static stall onset angle the dynamic lift increases beyond the maximum lift for quasi-steady conditions due to the unsteady boundary layer response and the effect of induced camber. Consequently, the effective pitch angle is lower than the instantaneous angle resulting in a delay in the onset of separation. More significantly, when separation occurs a strong vortex may be shed from the leading edge of the aerofoil which travels downstream thereby augmenting the lift of the section whilst the vortex remains above the aerofoil. When the vortex is shed from the trailing edge the lift decreases abruptly due to a state of full flow separation, often resulting in a lower lift than that corresponding to quasi-steady conditions. Flow reattachment can also occur at pitch angles lower than that corresponding to static stall onset due to the lag effects associated with the unsteady boundary layer response. The qualitative features of the dynamic stall process often remain similar for varying Reynolds numbers and forcing conditions, though the quantitative behaviour of the aerodynamic forces and moments show variations for different aerofoil shapes, thereby proving to be a challenge for low order numerical models. The degree of lift augmentation, the timing of vortex shedding, and the onset of vortex formation is dependent on factors such as the aerofoil shape, mean angle, amplitude and rate of oscillation, and compressibility effects. In general, three main categories of dynamic stall models that have been published in literature exist:

1. The actual kinematics of the process such as the time delay effects on leading edge pressure response, vortex formation, and vortex shedding are modelled (e.g., Beddoes–Leishman model);
2. The mechanics of the process are neglected, and the characteristics of the lift curve are modelled (e.g., ONERA model);
3. A reference pitch angle is introduced that mimics the effective pitch angle under dynamic conditions (e.g., Gormont model).

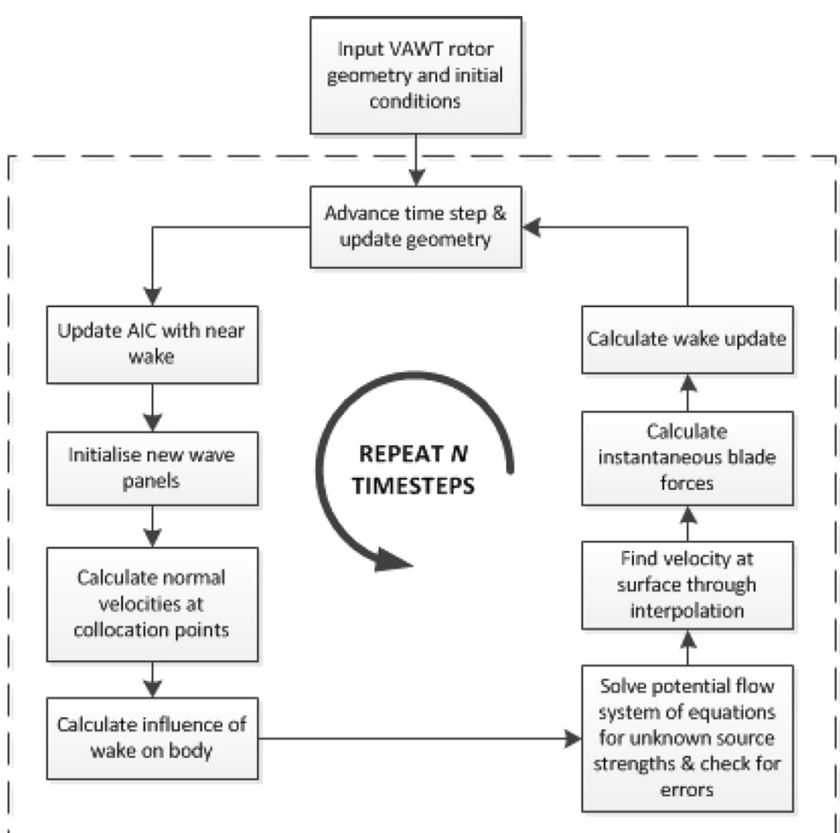

Fig. 11. Typical time-stepping scheme for panel models [58].

The Gormont model, initially developed for helicopter rotor applications, has been widely used in VAWT BEM models since it lends itself readily for implementation and has been shown to provide good accuracy. However it has been speculated that it over-predicts the effects of Dynamic Stall since the maximum angle of attack reached is generally higher than is typical for helicopter blades and a number of researchers have proposed a suitable damping coefficient to improve accuracy.

4.5.2. Tower shadow

Tower shadow can contribute to periodic fluctuations in electrical power output of both HAWTs and VAWTs due to a blade passing through the low momentum wake behind a tower. It is necessary therefore to locally modify the velocity field downstream of a tower to account for these losses, usually through an empirically derived correction factor.

4.5.3. Tip and junction losses

One of the major limitations of the original BEM theory is that there are no finite aspect ratio (i.e., 3D) considerations. Blade tips will shed vortices due to the pressure differential producing a local reduction in lift and an additional induced drag component. Similarly a horseshoe vortex is established at junctions of streamlined sections such as supporting struts that results in additional drag. Shires [32] proposed that a Prandtl lift loss factor, similar to that used within HAWT BEM models is also applicable for VAWT BEM models by applying a factor to the 2D lift coefficient based on the non-dimensional spanwise position, local angle of attack and the number of blades. Shires [32] also proposed an empirical relationship to determine the drag associated with secondary vortices in junction regions though this increment is comparatively small.

4.5.4. Flow curvature and expansion

The streamtube approach generally assumes a constant cross section is maintained through the rotor. Corrections are proposed for streamtube expansion [14] and curvature [45] though their effect on rotor performance is not significant.

4.5.5. Turbulent incident wind

Most numerical models of VAWT performance have assumed a rotor in steady and therefore artificial wind conditions. The effects of a stochastic wind profile on the dynamic response can be significant and should ideally be included in any analysis.

4.6. Other modelling approaches

Within the Aerospace community, CFD is routinely used for performance prediction in combination with experimental verification of designs in a wind tunnel. For Aerospace applications the RANS equations are generally solved or the Euler equations coupled with an appropriate empirical boundary-layer model. Whilst the steady state cruise performance of a complete aircraft can be performed with reasonable computational resources, the CFD analysis of a wind turbine is further complicated by the requirements for a time-dependant solution and the large range of complex flow physics experienced by the rotor with blades rapidly entering into and out of a deep stall condition. Due to the high requirements for computational resources CFD is consequently not routinely used for wind turbine analysis and lower order models remain the industry standard.

4.7. Discussion

In the BEM models, the assumption of quasi-steady flow may be violated by the complex flow field of floating wind turbines [47,49], thereby possibly rendering these models invalid. Another potential issue is that these models are not inherently developed for floating turbine applications, but for onshore wind turbines, whose oscillations in pitch and roll are orders of magnitude smaller than the ones experienced by floating wind turbine systems, and with virtually no heave oscillation (contrary to FOWTs). To evaluate the instantaneous loads acting on the rotor, a whole rotor revolution must be computed. Whilst some research has recently considered modifying the BEM model for floating applications [59] to allow for real-time interfacing with a hydrodynamic model, the models are currently not the most suitable for time-domain simulations.

As mentioned in §4.1, BEM models may break down at high tip speed ratios and when simulating high solidity rotors. Cascade models can be used in these situations to complement the BEM models, especially as they both follow very similar computational procedures. So far there has not been any research into whether cascade models can fully incorporate the unsteady, complex flow associated with floating wind turbines, although Mandal and Burton [39] did incorporate dynamic stall to improve numerical accuracy.

In spite of these drawbacks, the very efficient and quick execution times of these models have seen them maintain popularity. They should not be disposed of, as they can be an essential tool in the preliminary research and design of floating VAWT systems. BEM models can speed up the initial phases of a project by allowing a vast number of simulations to be carried out in a relatively short period of time, narrowing down the number of possible configurations and therefore allowing a more precise but more computationally demanding approach to focus on only the most promising configurations.

Whilst vortex models are deemed more accurate of than the two other models mentioned in this section [22], they require substantially more computation time than either the momentum or cascade models. This is an important factor in coupled-dynamics modelling, as the model has to execute as fast as possible, and has been the main reason vortex models have as yet not really been implemented in coupled dynamics codes for both VAWTs and HAWTs (except for Sebastian [49]). Attempts to modify the vortex model through vortex merging and other techniques by McIntosh and Babinsky [60] have improved computational efficiency whilst maintaining numerical accuracy and solution integrity. Whilst this work has been focused on small-scale VAWTs in urban areas, it could readily be applied in the offshore context.

Advances in desktop computational power and parallel computing have paved the way for much faster computation times of three-dimensional vortex models [61,62], with up to a 35.9 fold reduction over single processor times [62]. As discussed by Muskulus [63], vortex models are a viable option for use in coupled dynamics modelling of floating wind turbines. A shortcoming of this large reduction in computational time is that the model is required to be programmed in a language specific for multi-core processing units, but this can be overcome in programming environments such as MATLAB or using libraries for programming languages such as C or Fortran (see e.g. [64,65]).

Panel models offer the same advantages as the vortex models with regards to investigating rotor interactions with the near wake, multiple rotors operation in close proximity to one another, as well as novel rotors (possibly with multiple rotating bodies or pitching blades). It has yet to be seen whether panel models can compete with the previously described methods with regards to computation time, although parallel programming may significantly improve computational performance.

Ferreira and Scheurich [66] recently demonstrated that the power produced and instantaneous loads of a VAWT are decoupled. This

Table 1
Comparison of aerodynamic models.

	BEM model	Cascade model	Vortex model	Panel model
Complexity	Low-Medium	Low-Medium	Medium-High	High
Ease of implementation	Easy-Medium	Easy-Medium	Medium	Hard
Computational effort	Low	Low	Medium-High	Medium-High
Restricted to known aerofoils	Yes	Yes	Yes	No
Incorporate unsteady conditions	Limited	Limited	Yes	Yes
Rotor-wake/multiple rotor interactions	No/No	No/No	Yes/Limited	Yes/Yes

FAST	Bladed	ADAMS	HAWC2	3Dfloat	Simo	SESAM/DeepC
Code Developer						
NREL	GH	MSC + NREL + LUH	Risø-DTU	IFE-UMB	MARINTEK	DNV
OC3 Participant						
NREL + POSTECH	GH	NREL + LUH	Risø-DTU	IFE-UMB	MARINTEK	Acciona + NTNU
Aerodynamics						
(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW)	BEM	None
Hydrodynamics						
Airy+ + ME, Airy + PF + ME	(Airy+ or Stream) + ME	Airy+ + ME, Airy + PF + ME	Airy + ME	Airy + ME	Airy + PF + ME	Airy+ + ME, Airy + PF + ME
Control System (Servo)						
DLL, UD, SM	DLL	DLL, UD	DLL, UD, SM	UD	DLL	None
Structural Dynamics (Elastic)						
Turbine: FEMP + (Modal / MBS), Moorings: QSCE	Turbine: FEMP + (Modal / MBS), Moorings: UDFD	Turbine: MBS, Moorings: QSCE, UDFD	Turbine: MBS / FEM, Moorings: UDFD	Turbine: FEM, Moorings: FEM, UDFD	Turbine: MBS, Moorings: QSCE, MBS	Turbine: MBS, Moorings: QSCE, FEM

Airy+ – Airy wave theory; (+) with free surface connections
BEM – blade-element/momentum
DLL – external dynamic link library
DNV – Det Norsk Veritas
DS – dynamic stall
GDW – generalized dynamic wake
FEMP – finite-element method; (P) for mode preprocessing only
MBS – mulibody-dynamics formulation
ME – Morison's Software Corporation
PF – linear potential flow with radiation and diffraction
QSCE – quasi-static catenary equations
SM – interface to Simulink® with MATLAB®
UD – implementation through user-defined subroutine available
UDFD – implementation through user-defined force-displacement relationships

Fig. 12. Comparison of models used in current design codes for offshore HAWTs [70].

revelation may undermine the trend of validating codes through power curves, as whilst power prediction curves may be in very good agreement with experimental data, individual blade force predictions may not agree well with experimental data. This is seen in a number of papers when using BEM models [14], cascade models [39] and vortex models [45]. In the context of floating VAWTs it may be more suited to perform verification and validation based on blade force predictions rather power predictions.

Secondary effect models (in particular dynamic stall and flow curvature) have improved instantaneous blade force predictions for both momentum and vortex models, but discrepancies still exist. This aspect is rather important to consider when developing a coupled dynamics model for floating VAWTs as the blade forces shall affect system-level performance and any aeroelastic effects.[1]

Table 1 summarises the advantages and downfalls of the different aerodynamic models available for use within an efficient coupled model of dynamics in the design of floating VAWTs.

[1] Aeroelastic effects and modelling in the context of floating VAWTs are discussed in the companion paper on structural modelling for floating VAWTs, Borg et al. [73]

5. Current implementations

There have been a significant number of codes developed to analyse VAWTs by researchers around the world:

- Paraschivoiu [14] implemented the DMST momentum model in a code known as CARDAAX. Shires [32] also recently implemented a modified DMST model to evaluate more novel rotors, with emphasis on offshore applications [4].
- Strickland [27] developed two- and three-dimensional vortex models VDART2 and VDART3, respectively, in the 1970s as part of Sandia National Laboratories' efforts to develop VAWTs as a viable wind energy technology [10]. McIntosh and Babinsky [60] recently developed a very computationally efficient two-dimensional vortex model to investigate small-scale VAWTs deployed in urban areas that would have positive implications in the context of coupled dynamics modelling of floating VAWTs.
- Dixon [55] developed an unsteady three-dimensional panel model for VAWTs at Delft University of Technology that became known as UMPM (Unsteady free-wake Multi-body Panel Method). Whilst initially used for VAWTs in urban areas, it is now also being applied to large offshore VAWTs in collaboration with Sandia National Laboratories

In the context of coupled dynamics design codes for floating wind turbines, comparative studies by Jonkman and Musial [67], and Cordle and Jonkman [68,69] found that all major offshore wind design codes employ the BEM model as well as the generalised dynamic wake model in some cases, illustrated in Fig. 12 adapted from [67]. In fact, BEM models were used during the design of both the Hywind [2] and WindFloat [3] full scale prototypes. Whilst it is evident that BEM models are sufficient to design floating HAWTs, the inherently more complex aerodynamic nature described in the above sections indicate that momentum models are not as suitable for designing floating VAWTs. Sebastian [49] applied a free-vortex model coupled with NREL's FAST code for a floating HAWT. Whilst the authors were investigating the evolution of the wake of the rotor, it was not a fully coupled simulation and might have led to certain effects being ignored.

As yet these are restricted to HAWTs and no publicly-available coupled dynamics code exists for floating VAWTs that the authors are aware of, although Vita [19] applied the DMST momentum model coupled with the HAWC2 code to model a Darrieus turbine mounted on a rotating platform. The authors are currently developing an aero-hydro-servo-elastic coupled model of dynamics for floating VAWTs, and the development progress is outlined by Collu et al. [70]. Some example applications of this model for a floating VAWT with passive damping devices and combined with a wave energy converter have been presented by Borg et al. [71,72].

6. Conclusions

As highlighted in Section 2, the case for VAWTs deployed in deep offshore sites is evident as they seem to be more suitable that HAWTs to deliver a cost-effective wind energy solution. As part of furthering the development of this technology, it is essential to understand how the floating VAWT interacts with the offshore environment. As part of a series of articles, this article focussed on presenting a review on the different aerodynamic models suitable to be implemented as part of an efficient coupled model of dynamics for the preliminary design of floating VAWTs. The advantages and disadvantages of momentum-based models, vortex models and panel models, as well as modelling secondary effects such as dynamic stall and flow curvature were discussed.

The blade element momentum and cascade models provide very fast computational times and power predictions in good agreement with experimental data, but may fall short of adequately predicting instantaneous blade forces. As these models were originally developed for onshore VAWTs, their validity as quasi-steady approaches may be questioned when applied to floating VAWTs where unsteady flow conditions dominate. Despite these drawbacks, the ease of implementation and computational speed make these models very attractive and they have seen continued use by researchers.

Vortex and panel models are higher-fidelity models that are able to simulate the wake of the VAWT and can fully incorporate unsteady flow regimes, unlike the former two models. The ability to analyse interactions between the VAWT and its own wake as the platform oscillates, and the possibility of modelling a rotor (s) consisting of multiple rotating bodies are major advantages. These models can more accurately predict instantaneous blade forces and this may play an important role when considering aeroelasticity and the subsequent effects on system performance in terms of power generation and platform motion.

These models differentiate in the fact that vortex models still require lift/drag characteristics for known aerofoils, whilst in panel models any blade geometry can be modelled, enhancing the flexibility and potential of these types of aerodynamic models.

The cost of these higher-fidelity models is significantly increased computational times, which is an important factor when developing an efficient coupled model of dynamics for floating VAWTs. Recent trends towards high performance desktop PCs and parallel computing may drastically improve the computational performance of these models as discussed in §4.7.

As part one of a series of papers, part two focuses on modelling structural and mooring dynamics, and part three focuses on support structure hydrodynamics and approaches to developing coupled dynamics models for floating VAWTs.

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